Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 93 (2020) 131–136

www.elsevier.com/locate/procedia

53rd CIRP Conference on Manufacturing Systems

Automated assembly of Li-ion vehicle batteries: A feasibility study

Ryan D'Souza[a]*, John Patsavellas[a], Konstantinos Salonitis[a]

[a]Manufacturing Theme, Cranfield Univeristy, Cranfield, Bedfordshire, MK43 0AL, England, UK

* Corresponding author. Tel.: +447828205307;. E-mail address: dsouzaryanj@gmail.com

Abstract

Electric Vehicles (EVs) with rechargeable Lithium-Ion batteries (Li-ion) are at the forefront of the global trend for lower-emission transportation and decarbonisation. Capable suppliers of Li-Ion battery assembly systems are essential for enabling automotive OEMs to scale up their Li-ion EV production to expected volumes. This paper details a feasibility study for Li-Ion battery assembly, developed for a traditional automotive supplier of niche production systems in order to enable them to enter the emerging lower carbon OEM supply chains. Through simulation modelling, the essential components of a reconfigurable and scalable EV Li-ion batteries assembly system with provision for disassembly are explored and a generic framework is proposed.

Keywords: EV; Industry 4.0; Reconfigurable Manufacturing Systems; Flexible Manufacturing Systems; System Modelling; Manufacturing Line Design;

1. Introduction

With European governments aiming to ban Internal Combustion Engine (ICE) powered vehicles as soon as 2025, pressure is being placed on Original Equipment Manufacturers, (OEMs) to phase out traditional ICE vehicles in favour of alternative fuel. Electric Vehicles (EVs) are at the forefront of this evolution, with sales in rechargeable Lithium-ion (Li-ion) powered vehicles expected to increase from 2 million units in 2018 to 12 million in 2025 [1]. With majority of manufacturing capacity of Li-ion batteries found in North America and Asia, European governments are becoming increasingly aware that Europe is falling behind in both Li-ion battery manufacturing capacity and access to raw materials.

The primary drawbacks associated with EVs currently relate to range and the associated price per unit for vehicles. For OEMs to entice prospective buyers, these issues need to be addressed. EV battery packs accounts for roughly 30% of the total EV cost. Of this 30%, manufacturing accounts for 40% of the power unit cost [2]. This makes the manufacturing supply chain an ever important component with the aim of reducing EV costs in order to encourage adoption of EVs.

By developing a fully autonomous line which can adjust to variation in demand and conforms to lean principles will enable manufacturers to not only catch up to established manufacturing systems, but also be able to respond to varying demand. Furthermore, incorporating disassembly elements in to the assembly element will also address the sustainability concerns that the market is currently facing.

The aim of this paper is to develop a feasibility study for OEM suppliers with clear outlines on the essential components -through simulation- of a reconfigurable and scalable EV Li-ion battery assembly system with provision for disassembly.

2. Literature Review

2.1 Lithium Ion Batteries

Lithium ion batteries (LIB) are a type of battery that possess high specific energy, long life cycle and are highly efficient. They consist of an anode and cathode with a die-electric medium used to transport ions between the elements. LIB

10.1016/j.procir.2020.04.111

technology has been evolving very quickly, with OEMs looking to increase battery range whilst trying to ensure that the chemistry still remains stable. This has seen the development in Li-air and Solid-State Batteries (SSBs) with the latter being expected to become an established form of battery. SSBs have the potential to provide higher energy capacities, while being safer due to the solid electrolyte and is expected to be used commonly in the next decade. The anticipation of such technological evolution may be playing a role in delaying further investment into new manufacturing capacity of existing Li-ion production in Europe specifically.

2.2 Li-ion component and assembly

Li-ion batteries all have the same structure. They are composed of cells joined together to make a module, which are in turn, joined together to make a pack.

The battery cells contain the anode, cathode and electrolyte and come in three different designs. Prismatic cans, pouches and cylindrical designs. These cells, are then stacked and welded together to form modules. These modules can sometimes comprise of individual thermal management systems which are used to control cell temperature within the module. They modules are joined using ultrasonic welding and are then sent to be assembled into the overall battery pack.

The top level, of the Li-ion bill of materials is called the pack. The pack consists of multiple modules joined together, with mechanical fixings which allow for easier disassembly for servicing purposes. The pack also contains a battery management system which controls the thermal management system of each module.

Li-ion battery packs are complex systems. In addition to the materials required for the anode, cathode and electrolyte, they also require cooling systems, battery management systems, insulation packages, central module contractor systems, sensors and housing for both individual modules and the entire battery pack itself [3].

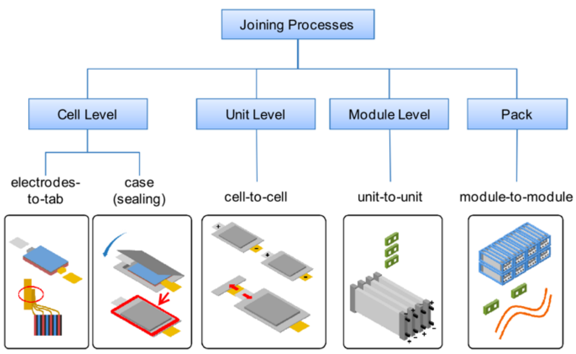


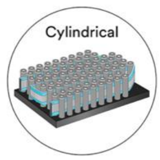
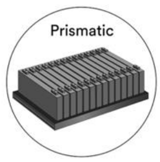
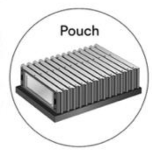
Figure 1: Automotive battery assembly packs, Lee et al. [4]

2.3 Cell Assembly

Historically, battery cells have used cylindrical designs. This design was used in mainstream market from alkaline battery cells to Nickel-Metal Hydrite (NiMH) battery cells. However, manufacturers have been trying to develop their own battery packs in order to optimise safety, power and lifecycle whilst doing so in a cost-effective manner. This has led to the development of three commonly used battery cell structures used in the automotive industry today. Cylindrical, prismatic metal can and pouch designs [4–7]. Each configuration plays a part in the orientation of each cell. A summary of these configurations can be found in Table 1 [6,7].

The general indication is that the majority of manufacturers will use the two different types of pouch cell design in battery packs. This is further underlined by reports that both Volkswagen and Audi will use prismatic can and pouched cells for their upcoming id.3 and e-tron vehicles respectively [8,9], given the size of the Volkswagen Group (VWG) it is assumed that the other OEMs under the VWG umbrella will also follow this strategy.

Table 1: Summary of Cell designs [6,7,10]

Cylindrical	Prismatic Metal Can	Pouch
Single large sheet of positive and negative electrodes and separator is stacked and wound. 	Wound electrodes pressed into ellipsoidal cross section formed into a flat shape. 	Electrode sheets are cut and stacked and connected using current collectors. 

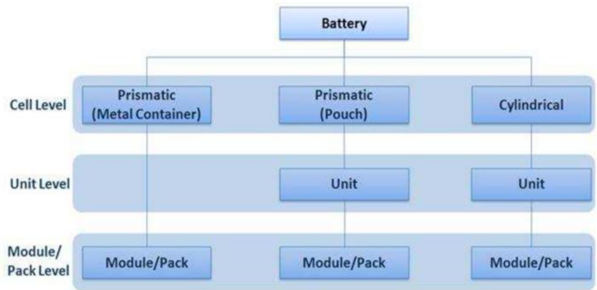


Figure 2: Types of lithium-ion batteries and their assemblies, Lee et al. [4]

2.4 Module Assembly

Module assembly is carried out in a similar way to that of unit assembly. Depending on whether the design requires a series or parallel configuration, module designs position negative and positive terminals on opposing ends or same end of each cell [6]. The cells are therefore joined by tab to tab or tab to bus bar connection. Ultrasonic welding is primarily used for this process as it allows for good quality welds across dissimilar materials and across multiple layers [7]. The module assembly process is summarised in Figure 3.

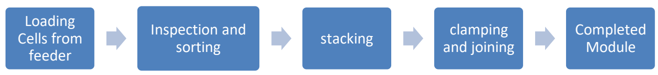


Figure 3: Processes for module assembly based on Hu [11]

2.5 Pack Assembly

The process for pack assembly is similar to that of the module assembly. However, in order to facilitate maintenance and repair, module to module connections are joined using mechanical joining with nuts/bolts or wires. The battery packs are tested, stacked and finally the modules are connected prior to testing. This process is outlined in Figure 4 below.

Figure 4: Processes for pack assembly based on Hu [11]

2.6 Battery Recycling

There are questions over the "cleanliness" of Li-ion power unit manufacture, and the future of "spent" battery cells. This not only affects future sustainability of supply chains, but can also greatly affect production costs.
The lifespan of a battery can be measured in two ways:

- In 'Calendar years' i.e. the length of time a battery can be stored with minimal discharge before its capacity diminishes.
- 'Cycle life' i.e. the number of charging and discharging cycles it can withstand before it becomes unsuitable for its application. Batteries are deemed suitable up until they can be charged to 80% of its initial capacity. After this point, battery capacity tends to degrade very quickly in a cascading effect [5].

End of life (EOL) batteries are expected to appear soon. They are expected to reach 120,000 to 170,000 tonnes per year by 2020. For this reason, questions remain over what will be done with these spent batteries. Especially as these batteries cannot be landfilled due to potential instability [12]. Furthermore, laws against the dumping of these batteries both by the EU [13] and more recently, the Chinese government have further incentivised battery recycling [14].

Many OEMs have released their strategies on 'second life' of spent batteries. These manufacturers have been installing used batteries, primarily as alternative means to energy storage systems.

Safely recycling battery packs requires expertise and special safety requirements to be met when disassembled. Additionally, with the different configuration of batteries present in today's market, recycling strategy would depend on the pack and the cell design. With many of these packs not assembled with disassembly in mind, governmental initiatives need to seek to change this in future [15].

Given that battery packs are not designed with disassembly in mind and coupled with the fact that there aren't many companies that specialise in the disassembly of these packs, the process of disassembly is likely to be costly.

Prior to recycling the cells, the packs need to be dismantled. This dismantling process entails removing cabling, the battery and thermal management systems and then breaking down the modules down to cells. Batteries are pre-processed by mechanical dismantling through shredding or cutting or via pyrometallurgy by smelting or pyrolysis [15]. This enables the extraction of copper and aluminium used in the cells themselves. Until recycling is fully carried out on a larger scale, it is yet to be determined which of these three process is the best way of separating materials.

However the complexity and economics of doing so seem to be unattractive to both OEM producers of batteries and the vehicle manufacturers themselves. As a result, vehicle capacity is lagging behind current supply of EVs. This has become a thorny sustainability issue.

2.7 Assembly Lines

With the expected demand for EV batteries set to increase in the near future and the persistent improvements in the power unit landscape, Manufacturing System (MS) designers face challenges of shorter product lifespans resulting in shorter production cycles and increased product mixes. Additionally with increased competition in today's EV market shorter lead times and improve on-time deliveries are becoming even more of a priority.

For this reason, the way assembly lines are designed, verified and phased in are extremely important. When a new line is built, layouts are first drawn up by manufacturing process engineers. These layouts are then simulated and verified using simulation carried out by productivity engineers [16].

In order for a manufacturing line to be able to provide the greatest benefit to OEMs and a potential aftermarket, having a reconfigurable assembly line that can not only assembly Li-ion components, but disassemble them too, this opens a market far beyond just manufacturing of new batteries. It opens a market for reconditioning, maintenance, recycling and remanufacturing. The connectivity afforded to manufacturing systems designers by industry 4.0 technologies, enables the design of synchronous manufacturing to real-time demand. This means that "holy grail" of a batch of one is now possible. Sensing the exact processing requirements of each individual unit as they flow through the production line can be achieved with reliable, inexpensive sensors and vision systems allowing the line to effect processing without paying a penalty on cycle times.

3. Research Methodology

Given the competitive and rapidly evolving nature of the current EV market, most of the information obtained relied on diverse sources, ranging from expert interviews, market analysis, industry publications and media reports. As a large component of this project was simulation based, the methodology for simulation studies developed by Banks, Jerry; Carson, John; Nelson Barry; Nichol, (2014) was also used.

4. Conceptual Model

Based on the understanding from the literature review of the supply chain of Li-ion battery composition and manufacturing processes, it was decided that the assembly line would focus primarily on module and pack assembly. However, information obtained through the interview with Dr. Colin Herron identified that some OEMs choose to use "graded cells". The intention of this is to group cells of similar chemistry together in modules, thus reducing the potential risk of issues due to cell performance compatibility. The literature confirmed that while some OEMs decide to carry out this practice, it was not widely adopted. This information was incorporated in the development of the conceptual layout and process diagrams.

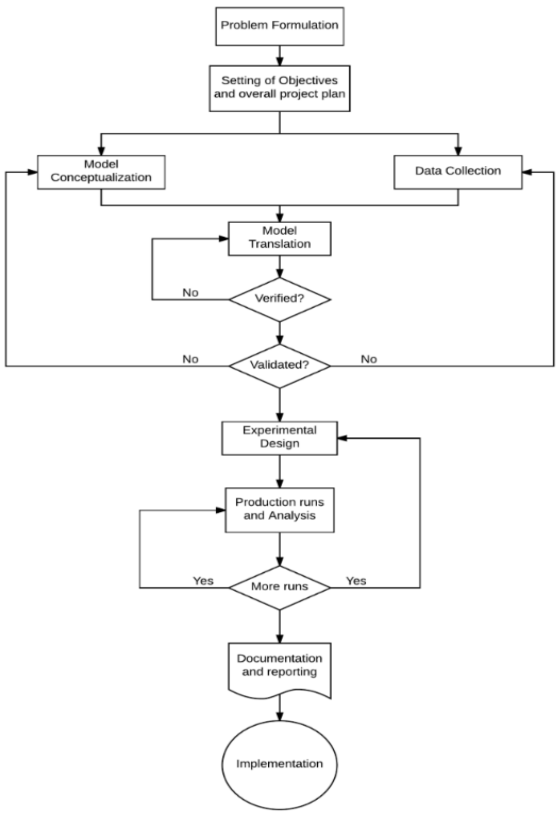


Figure 5: Modelling methodology developed by Banks et al. [17]

The model used a mixture of discrete event simulation (DES) modelling and agent based modelling (ABM). The model itself was built following common modelling methodology developed by Banks et al. [17]. The "virtual" manufacturing line model was built using the DES approach with events being created with the arrival of battery cells into the model. ABM was used to simulate the changing state of each element. Taking the example of the battery cell, Figure 6 shows 'state-charts' being used to show the battery cell in its multiple states. Overall the model contains three types of agents, namely battery cell, module and pack.

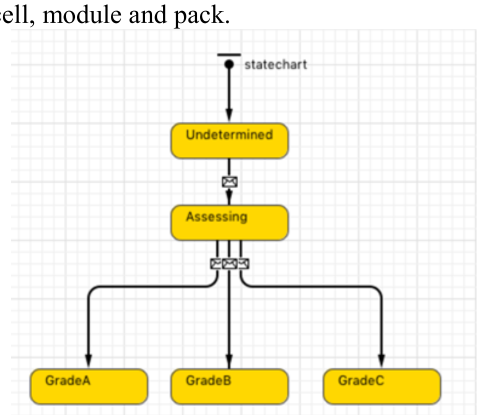


Figure 6: State-charts of a battery cell agent in AnyLogic simulation

5. Proposed Assembly Line

The proposed assembly line concept has been developed with the aim of filling the gaps in capability and requirements for the EV automotive sector in the assembly of Li-ion batteries. Using the data collected from the survey, accounts for potential requirements as required by industry. The concept consists of 6 modularised sectors with each sector capable of being scaled up and down in line with customer requirements. It aims to use flexible automation in terms of robotic arms and cobots with factory personnel, and relies strongly on the use of AGVs and conveyor systems to transport product around the production floor. Taking into account findings from the literature review, the concept is designed to handle prismatic battery cells and pouch cells. This allows for a reduced variation in tooling requirements in the handling of the battery cells.

5.1 Sector A

Sector A comprises of an entry conveyor (marked red) which feeds battery cells manufactured in another facility. At the entry conveyor, the cells are assessed. Once assessed, they are classified into Class A, Class B or Class C. At this stage, the battery will be sent down one of the three appropriate channels of the cell sorting area.

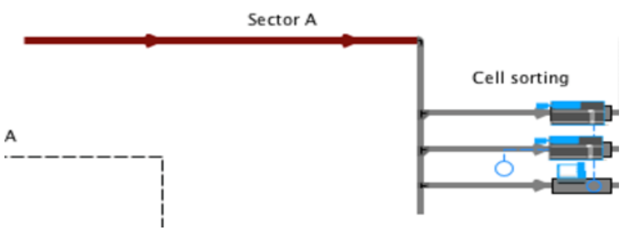


Figure 7: Sector A: Battery assessment

5.2 Sector B

Sector B consists of conveyors which transports the classified cells in batches of four into the module assembly area. Modules are stacked at the first station and then joined via welding. They are then transported from the node at the end of the conveyor to Sector C, the module inventory.

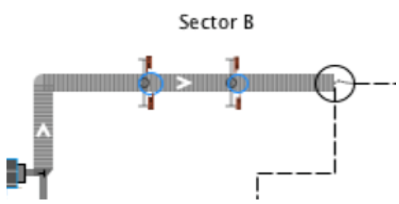


Figure 8: Sector B: Module assembly

5.3 Sector C

Sector C is the module inventory sector. Automated Guided Vehicles (AGVs) transport completed modules from Sector B to inventory. The inventory shelves themselves are developed to be modularised bins, which, once filled can be used in a 'lean supermarket' approach allowing OEMs improved control on inventory through lean initiatives.

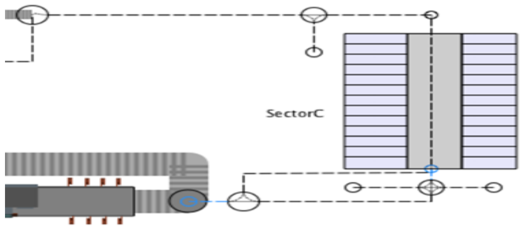


Figure 9: Sector C: Module inventory

5.4 Sector D

Sector D is the module stacking area. Eight modules, arrive to the staging area, where they are batched. At the first station they are joined together with the pack housing using mechanical fastenings. The pack housing is introduced from the smaller branched conveyor. They are then transported to the second work centre where the battery management and overall thermal management systems are introduced to the pack.

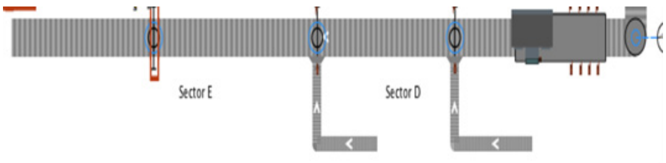


Figure 10: Sector D and E, pack assembly and inspection.

5.5 Sector E

The modules are then transported to sector E where the pack undergoes final inspection prior to being sent to the final vehicles assembly line.

5.6 Sector F

Sector F comprises of the disassembly section of the line. Battery packs are sent back up a line running parallel to the pack assembly line. The first work centre assess each module which then sets the conditions for diassembly at the following work centres. This inspection will dictate which modules are reusable and where can be sent for recycling. "DismantleA" removes the mechanical fixings, with AGVs being used to send scrapped items to recycling. The packs are then conveyed to "DismantleB" where the modules are separated from the busbars. "DismantleC" is where the modules are freed. They are then either sent back up to Sector C if deemed reusable or sent to recycle B to be recycled by vendors.

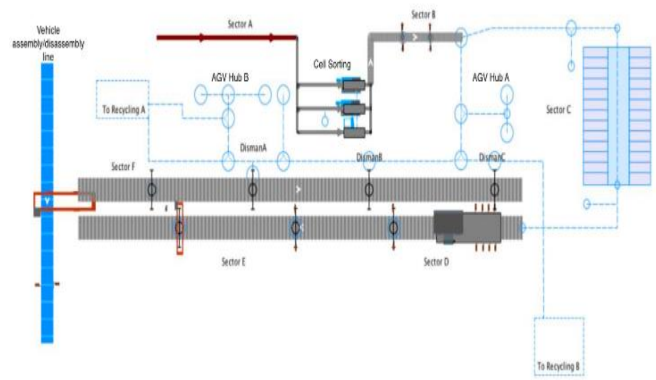


Figure 11: The assembly concept modelled using Anylogic.

6. Discussions and Conclussions

The concept developed is aimed to suit as many variations of battery module and pack design. For example, the line should be able to accommodate increased number of cells in a module, or increased number of modules in a pack. However, each solution will require a level of customisation to suit each client. The concept also incorporates components of all three type of assembly lines from the literature review, namely DMLs, FMSs, with a primary focus being placed on RMSs.

The proposed system is designed to help OEMs tackle the future challenges that the industry is expected to face imminently. It addresses the key design factors of scalability, complexity, modularity and reconfigurability, whilst also facilitating a solution regarding the "second life" and end of life of EV batteries.

It enables the homogenous classification of Li-ion battery cells to the module welding stage. The purpose of this is to maximise the lifespan of assembled modules and reduce the probability of premature module failure. It also enables the introduction of recycled/repurposed pouches. For example, a stack of class C cells could be reassembled together to enable the stable remanufacture of a new module.

By utilising latest developments in 5G wireless connectivity, the concept aims to allow for fast, wireless communication between the manufacturing system's sectors thus making the line industry 4.0 ready. This has the potential to allow the line to dynamically adapt to customer demand. For example, taking the current Ford line-up, the line could be programmed to build packs for the UK's two biggest selling models, the Fiesta and Focus. However, if dealerships suddenly see a spike in orders for the Mondeo model (which is assumed to require a higher power output) the line could automatically respond by changing the required tooling to the Mondeo pack variant.

The literature reviewed stated that majority of OEMs produce battery modules and packs in different facilities, sometimes even different continents. For this reason, the concept uses a buffer storage system between module and pack assembly, accommodating OEM strategies that may wish to follow a similar supply chain format. The inventory system provides the benefit that if module and pack assembly are completed in two different facilities, the storage can be designed to use modularised bins. The inventory system also caters for the possibility that OEMs may wish to consolidate manufacturing to one facility. In that case, an inventory system will most likely still be required, as a buffer of modules will ensure that the pack assembly line has the required "feed-stock" capacity should the pack configuration change to one that would require more modules. Vice versa, a product change to manufacture packs which require fewer modules will allow the inventory to act as a 'Kanban supermarket' which can initiate a pull production system and control overproduction. Furthermore, this inventory system could be placed between any other sectors along the line. For example, if battery cell classification and module assembly are completed in two different facilities or a buffer is required, the inventory system could be placed between these two sectors, thus creating the buffer required, which can provide the same lean benefits.

The concept also aims to address one of the biggest gaps found during the literature review, that of OEMs and battery manufacturers struggling to meet current and expected demand for batteries. Hardly any focus is being placed on how batteries can be dismantled and recycled. The developed concept addresses the issue, by adding a facility for pack dismantling and remanufacture. This follows the belief that, the same tooling and machinery used to assembly the packs can also be used to dismantle the packs to a modular level, which can be sent to recycling centres or reused to manufacture new packs. This allows OEMs or suppliers to potentially sell old battery cells back to battery makers who, in turn, can recycle the anode and cathode material to make new battery cells. This minimises the overall environmental impact, as less mining is required for virgin material. It could also reduce battery cell costs, with estimated savings of up to 51% on virgin materials [18] and would benefit OEMs greatly in making EVs more affordable. It also gives OEMs the opportunity to get ahead of any potential legislation that governments may deem necessary in future to encourage a closed loop supply chain. However, as discussed in the literature review, the main concern with regards to disassembly/remanufacture element of the line will be the condition in which packs are returned to manufacture. The main challenge will be to use tooling which will be able to account for variation in the packs being returned to the line. It is important to note that the proposed concept system is by no means a finished article.

The model validation was completed by engaging industry experts to scrutinise its results. The model was developed with multiple assumptions regarding the processes involved, cycle times and changeover times required to complete each process. Some concerns identified during validation were in relation to work-centres that had been assumed to constitute single assembly points. If these needed to be increased, requiring the product to be taken off the conveyor line for processing, it would add high levels of complexity to the design, therefore going forward carrying out sensitivity analysis of the assumptions made during this project should be a primary objective.

Due to the competitive nature of the industry, information on exact processes and the times required to carry them out are not published.

In the inherently complex practice of designing single purpose manufacturing assembly lines, the proposed solution offers a novel strategic capability of modular, scalable and sustainable value to the EV OEM sector. The whole design concept addresses current capacity needs in the EV sector, as well as unmet needs for long term sustainability of Lithium-ion power packs. Future work could entail using this concept to elicit more information into manufacturing practices and functional requirements for EV Li-ion battery packs, along with an iterative sensitivity analysis in order to test the impact of additional requirements on the model's robustness.

The work completed during this project could provide Li-ion assembly systems suppliers with a credible alternative concept proposition to engage with BEV OEMs and obtain more information about their manufacturing requirements for assembly and disassembly, volume plans and specs. This will allow for further details to be added to the model, thus allowing it to develop higher up the Technology Readiness Levels and eventually to a successful commercial product.

References

1. Wu H., Alberts G., Hoope J., Walton B. New market. New entrants. New challenges. Battery Electric Vehicles Contents. 2019. Available at: https://www2.deloitte.com/content/dam/Deloitte/uk/Documents/manufacturing/deloitte-uk-battery-electric-vehicles.pdf (Accessed: 8 June 2019)
2. Lebedeva N., Persio F Di., Boon-Brett L. Lithium ion battery value chain and related opportunities for Europe. 2016. Available at: https://ec.europa.eu/jrc (Accessed: 11 June 2019)
3. Kampker A., Heimes H., Lienemann C., Grauel D., Jones M. Development of a novel remanufacturing architecture for lithium-ion battery packs. 2017 Electric Vehicles International Conference, EV 2017. 2017; 2017-Janua: 1–6. Available at: DOI:10.1109/EV.2017.8242090
4. Lee SS., Kim TH., Hu SJ., Cai WW., Abell JA. A state-of-the-Art review on lithium-ion battery joining, assembly and packaging in battery electric vehicles. Evs 25. 2010;
5. Blomgren GE. The Development and Future of Lithium Ion Batteries. Journal of The Electrochemical Society. 2016; 164(1): A5019–A5025. Available at: DOI:10.1149/2.0251701jes
6. Lee SS., Kim TH., Hu SJ., Cai WW., Abell JA. Joining Technologies for Automotive Lithium-Ion Battery Manufacturing: A Review. ASME 2010 International Manufacturing Science and Engineering Conference, Volume 1. 2010. pp. 541–549. Available at: DOI:10.1115/MSEC2010-34168 (Accessed: 7 May 2019)
7. Das A., Li D., Williams D., Greenwood D. Joining Technologies for Automotive Battery Systems Manufacturing. World Electric Vehicle Journal. 2018; 9(2): 22. Available at: DOI:10.3390/wevj9020022
8. Kane M. Details On Audi's Battery Technology. Inside EVs. 2015. p. 1. Available at: https://insideevs.com/news/328601/details-on-audis-battery-technology/ (Accessed: 3 July 2019)
9. VolkswagenAG. The ID. Battery from Volkswagen. Volkswagen AG. 2019. Available at: https://www.volkswagenag.com/en/news/stories/2018/10/powerful-and-scalable-the-new-id-battery-system.html (Accessed: 3 July 2019)
10. 3M. Electric Vehicle (EV) Battery Solutions - Automotive | 3M US. 3M science. 2018. Available at: https://www.3m.com/3M/en_US/oem-tier-us/applications/propulsion/ev-battery/ (Accessed: 27 August 2019)
11. Hu J. Lithium- ion Battery Manufacturing. Michigan; Available at: http://www.mpoweruk.com/chemistries.htm] (Accessed: 11 June 2019)
12. Science for Environment Policy Science for Environment Policy Towards the battery of the future About Science for Environment Policy. 2018; Available at: DOI:10.2779/503230 (Accessed: 18 June 2019)
13. Stringer D., Ma J. Where 3 Million Electric Vehicle Batteries Will Go When They Retire - Bloomberg. Bloomber BusinessWeek. 2018. Available at: https://www.bloomberg.com/news/features/2018-06-27/where-3-million-electric-vehicle-batteries-will-go-when-they-retire (Accessed: 19 June 2019)
14. BloombergNEF. EVO 2019. Bloomberg. 2019. p. 8. Available at: https://bnef.turtl.co/story/evo2019?sf103682979=1 (Accessed: 7 June 2019)
15. Eric Melin H. The lithium-ion battery end-of-life market-A baseline study. 2018. Available at: http://www3.weforum.org/docs/GBA_EOL_baseline_Circular_Energy_Storage.pdf (Accessed: 19 June 2019)
16. Tjahjono B., Ball P., Ladbrook J., Kay J. ASSEMBLY LINE DESIGN PRINCIPLES USING SIX SIGMA AND SIMULATION. Available at: https://www.informs-sim.org/wsc09papers/298.pdf (Accessed: 20 June 2019)
17. Banks, Jerry; Carson, John; Nelson Barry; Nichol D. Discrete-event system simulation. 5th edn. Pearson; 2014.
18. Mayyas A., Steward D., Mann M. The case for recycling: Overview and challenges in the material supply chain for automotive li-ion batteries. Sustainable Materials and Technologies. Elsevier; 1 April 2019; 19: e00087. Available at: DOI:10.1016/J.SUSMAT.2018.E00087 (Accessed: 17 May 2019)

2020-09-22

Automated assembly of Li-ion vehicle batteries: A feasibility study

þÿD S o u z a ,   R y a n

Elsevier

D'Souza R, Patsavellas J, Salonitis K. (2020) Automated assembly of Li-ion vehicle batteries: A feasibility study. Procedia CIRP, Volume 93, 2020, pp. 131-136

https://doi.org/10.1016/j.procir.2020.04.111